Aramid Fibres for Civil-Engineering Applications

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44.1 Introduction

Aramid fibres are one of the high performance modern fibres[1] that are potentially of interest to civil and structural engineers, being characterized by high strength, high stiffness, low creep and resistance to corrosion. Unlike carbon and glass fibres, however, the aramid fibres are frequently used without resin impregnation, since they are much more resistant to local bending effects.

The term aramid is used to refer to aromatic polyamides containing chains of aromatic (benzene) rings, linked together with —CO— and —NH— end groups. Many forms can be produced,[2] but those based on *para* links on the aromatic ring generally give the strongest fibres.

These fibres are now available under a variety of commercial trade names, such as Kevlar (manufactured by Du Pont in America and Northern Ireland), Twaron (manufactured by Akzo in The Netherlands) and Technora (manufactured by Teijin in Japan). The fibres have a modulus greater than 40 kN mm^{-2}, and so fall within the high-performance category.[3] This category effectively excludes conventional textile fibres, nylon and polyethylene, on the basis of either strength, stiffness or creep.

The author has been involved with the testing of these materials for many years, primarily in the form of parallel-lay ropes, and much of the information presented here is based on that work. Some of the review material is taken from the Ph.D. theses of his co-workers Chambers[4] and Guimaraes,[5] and their permission to use that material is gratefully acknowledged. Valuable assistance has also been provided by various people at Du Pont, Akzo and Teijin.

44.2 Development

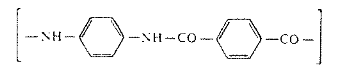
Du Pont produced the aramid fibre Nomex, poly(*m*-phenylene isophthalamide), in 1958, and research increased on other aramid fibres by this company and its competitors. A concentrated research effort by Du Pont led to the discovery of the precursor to Kevlar in 1965. This was known as Fibre B and was based on poly(*p*-benzamide);[6] it may be produced by either wet- or dry-spinning procedures. The development of Fibre B now appears to have been halted, however, probably owing to the high cost of the starting monomer (*p*-aminobenzoic acid) and the limited stability of the spinning dope.

The Kevlar polymer, poly(*p*-phenylene terephthalamide) or PPT, had been prepared as early as 1958, but the existing spinning techniques had failed to produce a high-strength fibre. It was known, however, that PPT polymer dissolved in concentrated sulphuric acid, and so when a technique for spinning from strong acids became available, the preparation of PPT fibres was reconsidered. When the well-known dry-jet wet-spinning process was used in conjunction with a sulphuric acid spinning dope, a PPT fibre was produced with properties that surpassed those of previous developments. Furthermore, this new breakthrough also led to increased productivity and considerable cost savings. Hence, the registered name of Kevlar was announced by Du Pont in 1973 to replace that of Fibre B.

44.3 Current production processes

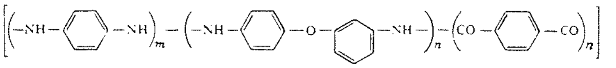
Two routes are now used for the production of aramid fibres. Twaron and Kevlar are produced by a refined version of the original process, while Technora is produced by a different process which results in a fibre with slightly different properties. Twaron is virtually identical to Kevlar, and in the rest of this chapter the two materials will be treated as identical, unless otherwise stated. Technora is slightly different both chemically and physically; as far as its uses as an engineering material are concerned, however, the properties are similar to those of Kevlar. Once again, therefore, only the differences from Kevlar will be highlighted.

Kevlar and Twaron are prepared by the reaction of terephthaloyl chloride and *p*-phenylene diamine under carefully controlled conditions.[2] The polymerization takes place in a dialkyl amide solution; after drying, the polymer is dissolved in concentrated sulphuric acid, from which the fibres are spun. The fibres are washed to remove the acid, and then heat treated. By varying the degree of heat treatment given to the washed fibres, considerable variation in the Young's modulus and elongation can be produced. Du Pont produce a number of different types of the same basic Kevlar fibre, each intended for specific applications, while Akzo produce two versions of Twaron. Kevlar 29, Kevlar 49 (formerly PRD-49) and Kevlar 149 (or Kevlar 'HM') from Du Pont, and Twaron and Twaron HM from Akzo are the fibres of particular relevance to civil engineering. The chemical structure is a polymer of a single repeating unit, hence the chemical name poly(*p*-phenylene terephthalamide), and the structure:



Kevlar and Twaron filaments are a translucent straw colour and have a diameter of 0.012 mm, but this size is too small for practical use. The material is commercially available in the form of multifilament yarns of varying size and with a range of finishes. Woven fabric, rovings and staple fibre are also available. Most test results are quoted for 1000 filament yarns, and care is needed when comparing test results to distinguish carefully between filament and yarn results.

Technora is a co-polymer, made up of two monomer units. One is the same as the other fibres, while the other (diaminodiphenyl ether) contains an extra benzene ring, giving co-poly-(*p*-phenylene/3,4′-diphenyl ether terephthalamide) with the structure:[2]



The object of the change is to make possible the use of general organic solvents, rather than the concentrated sulphuric acid used in the original process. The solvent used is *N*-methylpyroridone (NMP), and the amorphous polymer is spun into a coagulating bath, and then drawn. Significantly, it is believed that the crystallization takes place after the spinning process, but before drawing. It is claimed that this means that, although the degree of crystallinity is similar in the two fibres, in Kevlar and Twaron the boundaries between the crystals occur in groups, giving a weaker area of amorphous material, whereas in Technora the crystal boundaries are arranged randomly throughout the fibre.[6]

Development of aramid fibres has not yet finished. Refinements of the production process will be made in an attempt to improve the quality of the product, with associated enhancements of both strength and stiffness. At the same time, different chemical structures are also being considered, with a variety of different chemical groups being placed between the aromatic rings. The best properties have been reported for aromatic heterocyclic polymers;[1,2] polybenzobisoxazole (PBO) has been produced with a strength of 3400 N mm^{-2} and a stiffness of 340 kN mm^{-2}. These particular fibres are only available in small quantities, and the costs are such that their use is restricted to very specialist applications at present.

44.4 Properties of aramid yarns

The properties possessed by aramid yarns are summarized below. Some of the descriptions are relative to the properties of other fibres, rather than to the properties of metals, but they serve as a starting point for more detailed consideration of the materials:

(1) high tensile strength;
(2) high stiffness;
(3) high specific strength;
(4) low density;
(5) low creep;
(6) finite life when subjected to high stresses;
(7) excellent longitudinal tensile fatigue performance;
(8) good shock-loading performance;
(9) poor compressive strength;
(10) moderate abrasion resistance;
(11) good chemical resistance;
(12) poor ultraviolet resistance;
(13) resistance to high temperature;
(14) relatively good thermal stability; and
(15) electrical non-conductivity.

Kevlar has been in production since 1972, and the other fibres were produced soon after, so their properties are well documented. There appears to be considerable inconsistency in the results reported in the literature, however, owing to:

(1) confusion over the particular type and grade of aramid studied;
(2) the lack of differentiation between filaments, yarns, and ropes;
(3) the adoption of a multiplicity of testing techniques; and
(4) use of a variety of measures, such as mean, minimum or characteristic values, for quantities which are variable.

For these reasons, therefore, some care needs to be taken in interpreting the published test data.

The detailed accounts of Kevlar properties given by Du Pont[7–9] and by a number of authors[10–14] have all originated from Du Pont laboratories or are based on Du Pont published data and more consistency in the results reported in these references is observed. A recent monograph[2] contains a thorough review of Kevlar and Technora properties, together with those of other aromatic high-strength fibres.

44.4.1 Tensile properties

The tensile properties of aramid yarn and alternative reinforcement materials are shown in *Table 44.1*; the specific strength of the aramids is greater than for any other commercially available fibre, apart from carbon fibres. This makes them very suitable for weight-sensitive applications, such as in the aerospace industry. Aramids also have an initial tensile strength greater than steel and a longitudinal stiffness of the same order.

Approximate stress–strain curves for the aramids are virtually linear and display negligible plastic deformation prior to failure as shown in *Figure 44.1*.

44.4.2 Creep

The creep of aramid fibres is generally considered to be a logarithmic function of time; creep rates are low when compared with other synthetic fibres such as nylon or polyester and they approach that of steel. Early work[15] indicated that the creep rates for yarns of Kevlar are fairly insensitive to loads between 20% and 50% of the ultimate load but that they decrease at lower loads. Creep rates of 0.02% and 0.052% per decade were observed at room temperature for Kevlar 49 and Kevlar 29,

Table 44.1 Comparative tensile properties*

	Ultimate tensile strength (N mm^{-2})	*Strain at ultimate* (%)	*Initial modulus* (kN mm^{-2})	*Specific gravity*	*Specific strength*†
Aramids					
Kevlar 149	2410	1.4	146	1.47	1.64
Kevlar 49	2900	1.9	120	1.44	1.92
Kevlar 29	2900	3.7	58	1.44	1.92
Twaron	2800	3.3	80	1.44	1.94
Twaron HM	2800	2.0	115	1.45	1.93
Technora	3100	4.4	71	1.39	2.23
Non-aramids					
Nylon	990	18.3	6	1.14	0.87
Polyester	1120	14.3	14	1.38	0.81
E-Glass	2500	4.0	70	2.6	0.96
S-Glass	4600	5.5	85	2.5	1.84
Carbon fibre	2200–5400	0.4–1.8	238–444	1.76–1.9	1.13–3.00
PBO	3400	1.0	340	1.5	2.27
Boron fibre	3150	0.8	379	2.49	1.27
Mild steel	300	20.0	200	7.85	0.03
Prestressing steel	1700	1.6	200	7.85	0.22

* Figures in this table should be taken as a guide only. For most fibres, even more than for bulk materials, final properties are heavily dependent on the size of the fibre and the exact details of the production process, as the wide range for carbon fibres makes clear.
† Specific strength = tensile strength/density.

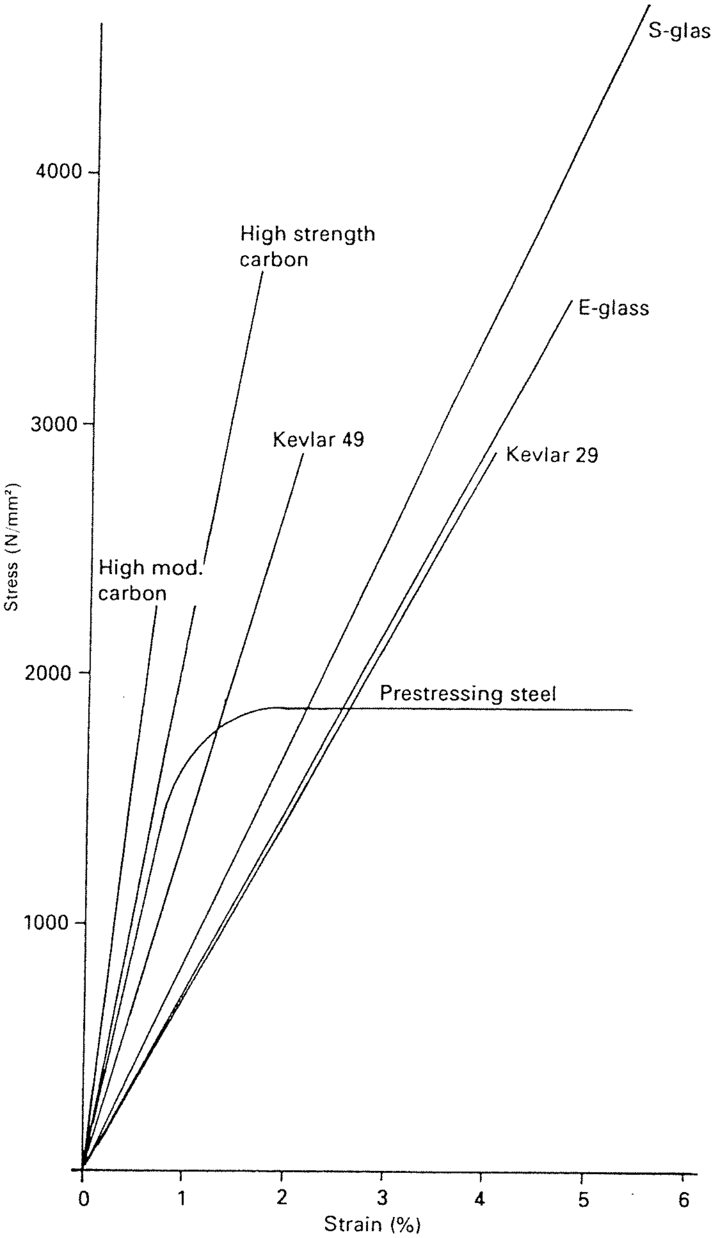


Figure 44.1 Typical stress–strain curves for aramid and some comparable alternative materials. Note that for most of these materials a wide spread of values can result from changes in details of the production process. Actual fibre tests show slight non-linearities in most cases

respectively (one decade is equivalent to one unit on a log time-scale to base 10).

Other workers have found that the rate of creep is stress dependent. Schaefgen[13] refers to work by Blades who observed a linear dependence of the creep rate with stress. Similarly, Ericksen[16,17] has found that the creep rate for Kevlar displays an increasing trend with stress. Considerable work has now been undertaken on long-term creep behaviour by Guimaraes,[5] who agreed with Blades; this is also in accordance with data published on Twaron.[18]

Work continues to extend the creep data available, but for all practical purposes it can be concluded that the creep strain over the lifetime of the structure in any application is unlikely to exceed 0.15%,[4] which is very small.

44.4.3 Stress rupture

When some materials are subjected to permanently applied loads they eventually creep to failure. This phenomenon is generally referred to as stress rupture. Considerable attention has been paid to the stress-rupture behaviour of Kevlar yarns.[19–21] In all cases it was found that Kevlar yarns would support a large proportion of their nominal short-term ultimate loadings for long periods of time, but that there was considerable variability in the stress-rupture lifetimes for any given load level.

The 'time-to-failure' under the dead-weight loading for aramids is superior to nylon and polyethylene[11] and by extrapolating the results of short-term stress-rupture tests on a logarithmic scale with time it has been suggested that yarns of

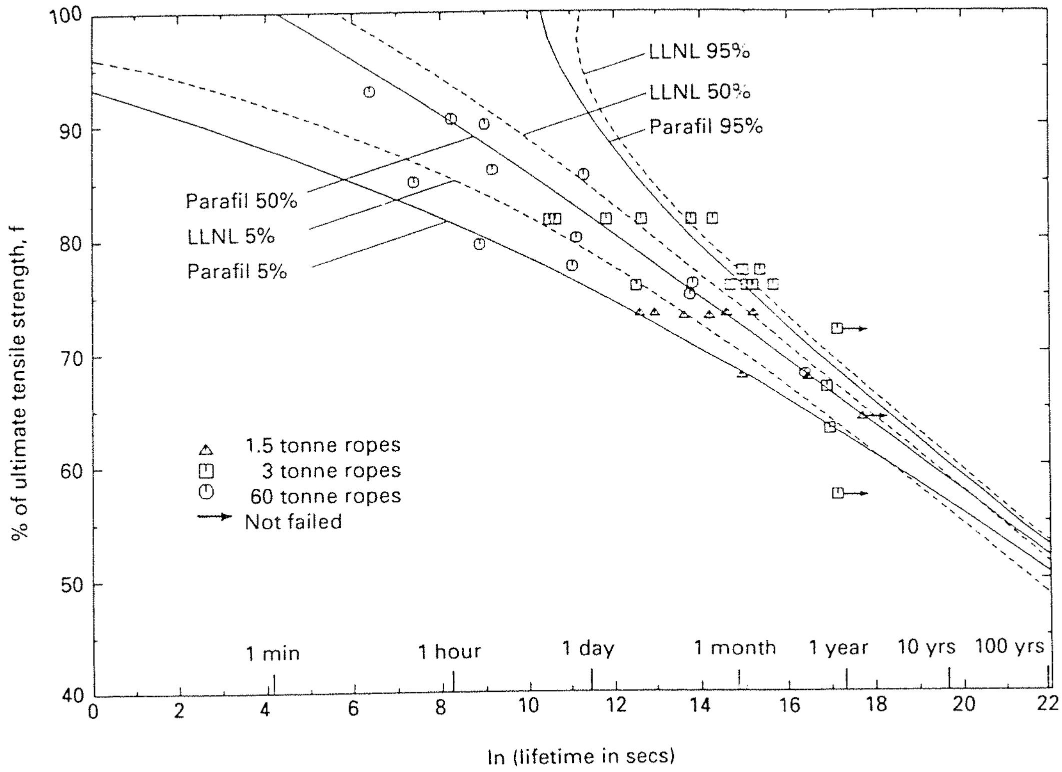


Figure 44.2 Stress-rupture data for parallel-lay aramid ropes (Parafil) made from Kevlar 49 yarn (taken from Guimaraes[5]). (——) 5%, 50% and 95% probabilities of failure based on rope tests; (- - - -) similar predictions based on Kevlar 49/epoxy composites at the Lawrence Livermore National Laboratory (LLNL)

aramid will support a load of half their breaking strength for over 100 years.

Considerable data have now been obtained for the stress-rupture behaviour of parallel-lay aramid ropes;[5,22,23] the most recent data[5] show that the mean load to give failure after 100 years is about 52% of the short-term breaking strength, and allowing for the variability of the material, it is predicted that a load of 46% of the initial breaking load will have only a 10^{-6} probability of failure after 100 years. Such figures indicate that stress rupture must be taken into account, but is unlikely to prevent the material's use in practical, long-term, applications. *Figure 44.2* shows 'time-to-break' against applied load for these ropes, and also theoretical predictions for longer term loads. The curves marked 'LLNL' refer to predictions[4] based on a large number of tests carried out at the Lawrence Livermore National Laboratory[19] on Kevlar/epoxy composite rods; the results compare well with the tests on the parallel-lay ropes.

44.4.4 Tension–tension fatigue

The fatigue performance of Kevlar has been studied,[10,11,24,25] although some of the studies were limited to the preproduction fibre PRD-49.[24] A summary of much of the research into fatigue is given in *Figure 44.3* where the fatigue performances of Kevlar and other reinforcement materials are indicated in the form of *S–N* curves which relate peak stress to the number of cycles which the material can withstand. The relative flatness of the *S–N* curves for Kevlar is an indication of the material's good fatigue performance.

The tension–tension fatigue resistance of Kevlar (when cycling between a lower and a higher tensile force) is superior to steel. Indeed, a zero twist yarn of Kevlar 49 will run for 10 million cycles when stressed between 170 and 1700 N mm^{-2}, whereas the stresses for steel wire have to be confined to the range 100–1000 N mm^{-2} to produce failure after an equivalent number of cycles. As a result, some authors[11] have concluded that tensile fatigue is unlikely to be a limiting design criterion for typical applications of Kevlar.

There is some evidence that 'fatigue' is not a sensible measure of resistance to cyclic loads for many polymers. Tests,[26] made primarily on nylon fibres, have indicated that it was the total duration of the loading that was significant, not the number of cycles. Thus, 10 000 cycles at 10 Hz is as damaging to the fibres as 1000 cycles of the same amplitude at 1 Hz. A cumulative damage rule, based on creep-rupture data, may well prove to be the best criterion for estimating failure under cyclic loads. Some work was done in the same study on Kevlar 49, and similar results were obtained.

Tension–tension tests[27] and tension-bending tests[28] on parallel-lay aramid ropes have also shown good fatigue properties when the fibres are assembled into practical elements.

44.4.5 Impact and shock-loading resistance

The breaking strengths for Kevlar at high loading rates are comparable to, or slightly higher than, those at normal rates;[11] the energy absorption at failure in Kevlar is about half that in nylon, while the repeated shock loading of a Kevlar rope (up to 40% of its nominal breaking strength) resulted in only a 13% reduction in strength after 100 000 cycles. In addition, Kevlar 29 and Kevlar 49 have performed well in typical ballistic

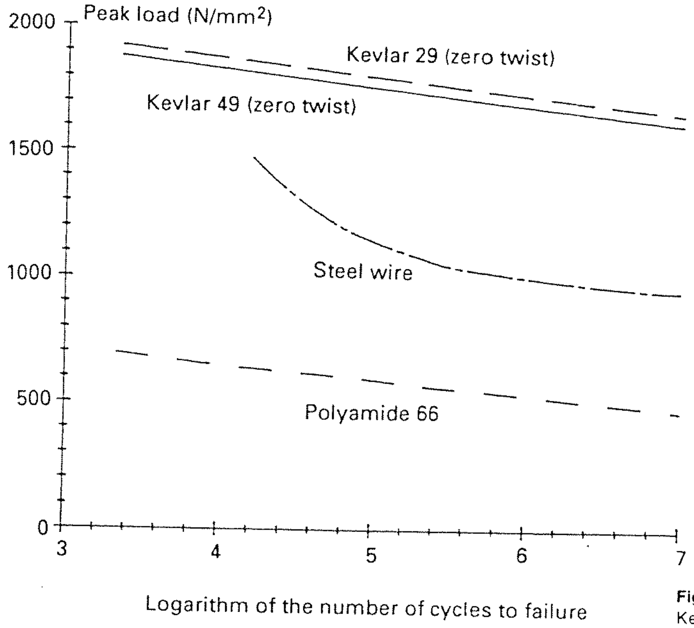


Figure 44.3 *S–N* curve for tension–tension fatigue fracture of Kevlar yarn. (Redrawn from Ferer and Swenson[11])

applications, and are widely used to manufacture bullet-proof clothing.

Kevlar may be prone to shock damage, however, if subjected to a sudden release of tension.[29,30] The rapid 'snap-back' probably produces a compressive wave and so the damage may possibly be attributed to Kevlar's weak compressive strength (q.v.).

These results and extensions to practical applications depend on the structure of the material; rope structure (parallel, braided or laid), or the presence of an epoxy matrix, will have a significant effect.

44.4.6 Compressive strength

The compressive strength of Kevlar is likely to be of importance when it is incorporated into a rigid composite, typically with epoxy resin. The ratio of tensile strength to compressive strength is about 5:1.[11,31] This poor performance is apparently due to weak lateral cohesion between the rigid longitudinal molecular chains. Kink bands (which appear to represent a shear failure across the fibre, but in fact are caused by buckling of the individual elements of the fibre) were observed using scanning electron microscopy.[31]

Practical applications of aramids will normally aim to use aramid fibres aggregated into larger elements, and to make use of the tensile strength of the fibres. Compressive stresses will only normally be developed in the terminations of such elements. Parallel-lay ropes are normally anchored by means of a termination which relies on compressive forces being developed across the fibres; these are kept at a sufficiently low and reliable anchorages have been formed in this way.[32]

44.4.7 Abrasion resistance

The moderate abrasion resistance of aramids may be a potential limitation in some applications;[25] indeed, in their raw state, it is inferior to that of nylon or polyester. However, the abrasion performance of aramid yarns can be improved considerably by the use of yarn finishes (special coatings, usually oil based) and when a combination of yarn twist, epoxy impregnation and wax overlay is adopted. As a result, all manufacturers now produce yarns with alternative finishes. A 'standard' finish is often applied to aid yarn processing, while for rope and cable applications, where abrasion performance is especially important, a special high lubricity finish is available. For applications such as the strength element in fibre optic cables, yarns with no applied finish can be supplied.

44.4.8 Chemical and environmental resistance

The chemical resistance of aramid is outstanding except for prolonged exposure to some strong mineral acids and alkalis. Teijin claim that the resistance of their co-polymer fibre Technora is significantly better than that of the single-polymer fibres, due to the different manufacturing process, which leaves much smaller areas of amorphous material through which chemicals can penetrate.

The rate of hydrolytic degradation at 100% relative humidity at room temperature, has been estimated to be less than 1% per year,[33] and no significant loss in tensile strength is reported for both Kevlar 29 and Kevlar 49 after three years exposure to seawater.[15] All aramids are degraded substantially, however, when subjected to sources of ultraviolet radiation, (e.g. sunlight); there is some self-screening for the bulkier products but, nevertheless, external jacketing is recommended for maximum durability.

A study of the 'ageing' of Kevlar in various environments confirmed that the loss of strength is small when Kevlar is exposed to seawater and a variety of chemicals.[34]

44.4.9 Temperature effects

Only small reductions in the tensile strength of Kevlar are observed[7,8] up to a temperature of 180°C. Beyond this temperature, however, significant reductions in strength are recorded. *Figure 44.4* illustrates the thermal stability of Kevlar 49 when exposed to elevated temperatures up to 250°C for prolonged periods.[8] Despite the strength loss at high temperatures, aramids do not melt or support combustion;[35] indeed,

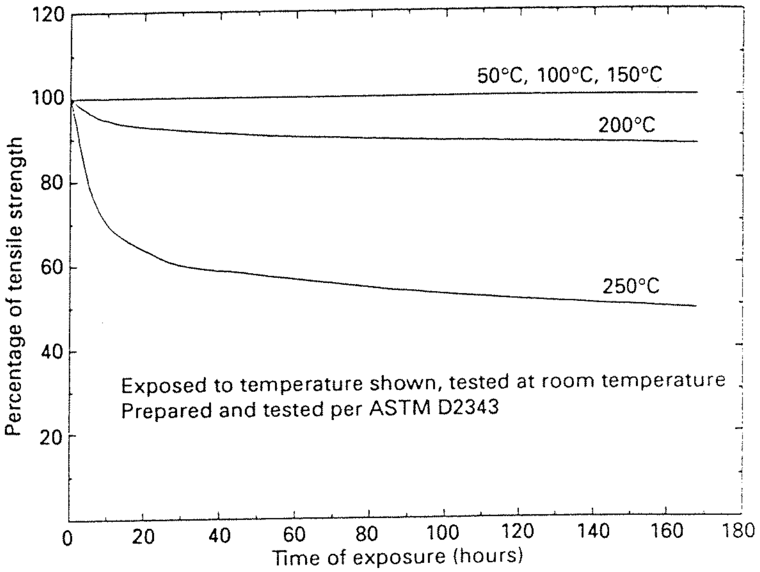


Figure 44.4 Effect of prolonged high temperature on strength of Kevlar 49 yarns. (Redrawn from Du Pont[8])

the material may be described as flame-retardant and self-extinguishing.

At cryogenic temperatures (−170°C) the material does not embrittle or lose its properties. In fact, under arctic conditions a slight increase in the tensile strength and modulus of Kevlar has been observed[10] and good resistance to thermal shock (−196°C to +196°C) is reported.[34]

The thermal expansion of Kevlar 49 yarns has been studied when subjected to stress.[5] It was found that, not only did the material contract as the temperature increased, as do many polymers, but the coefficient of linear thermal expansion became more negative as the stress level increased. However, it was also found that the thermal conductivity was very low, and this may explain why tests aimed at determining the thermal expansion of ropes made from Kevlar have detected much smaller changes in length.[36]

44.5 Applications

The properties of the aramid fibres clearly makes them suitable for many applications. All the manufacturers produce a range of literature describing the uses to which the material may be put. Many of these applications are obvious ones for high-strength fibres, for example in fabrics and nets. The high stiffness and low creep of the fibres means that they are now used in high-performance yacht sails, where the shape has to be maintained under a variety of wind conditions. The good resistance to shock loads, as well as the light weight, strength and stiffness also means that the fibres are widely used in personnel protection clothing, such as bullet-proof vests.

Aramid fibres are frequently used as reinforcement for rubber, in tyres, webbing and conveyor belts. An increasing use is as a resin-based composite for the aerospace industry. Quite extensive experience has been built up with non-load-bearing panels, and now structural panels are being incorporated in modern aircraft. The fibres can be used in the form of continuous yarns, or as chopped filaments, in which form the components can be formed in injection moulding or extrusion moulding machines.

For applications where larger forces are required, the fibres have to be aggregated into larger units. Traditionally, the way this has been done, for conventional fibres, is in the form of ropes which are braided or twisted together. Such ropes have also been made from aramid yarns and are quite widely used in the marine and offshore industries, where the high strength and low creep are desirable properties.[25,37] Many forms of rope construction are used, including composite ropes in which aramid fibres provide the strength to an electrical or optical fibre conductor.

For civil and structural engineering, a number of applications can be considered. These will be considered in more detail below. A summary of proposed applications for aramids, which includes both construction and other applications, is given in *Table 44.2*.

44.5.1 Applications in civil and structural engineering

Civil and structural engineering applications differ from many of the other applications in several ways. The loads are generally higher, with forces to be resisted of the order of tens, if not hundreds, of tonnes. The loads are often of long duration (years not hours), and long-term stiffness (including both elastic stiffness and creep effects) is very often the governing criterion. To be effective, the yarns need to be aggregated together into a sufficiently large unit to apply a significant force. Several methods of achieving this will be considered in more detail below.

44.5.1.1 Pultruded sections

Pultruded sections are produced by drawing fibres through a die (of appropriate shape) in which resin is injected. A variety of fibres can be used, including glass, carbon and aramid. Many cross-sections are possible, including I-beams, box-beams and special sections for particular applications. In addition to the shape, the designer can choose the type of fibre to use, which need not be the same in different parts of the section. Thus, it is possible to have a section with aramid fibres in the tension zone and carbon fibres in the compression zone, where the aramid fibres would be unsuitable. It is also possible to use woven tapes with fibres at specified angles, to give resistance to shearing forces. Most civil engineering applications to date have used glass fibres,[38] but specialist pultrusions with aramid fibres are also likely to be used commercially soon.

These sections are relatively easy to produce, but the principal

Table 44.2 Applications of aramids and aramid composites

Ropes and cables Mooring lines Guy ropes Balloon tethers Oil rig risers Tensioner lines Pendant lines Electromechanical cables	*Structural engineering* Pultruded beams Reinforcement for concrete Prestressing tendons Stay cables for bridges
Aircraft/aerospace Panels, flooring Escape slides Pressure vessels Rocket motor cases Propellor and helicopter blades Parachutes	*Automotive* Car body panels Truck chassis beams (hybrid with carbon fibre) Brake linings Clutch facings Gaskets Hoses and belts Belts in tyres
Industrial Conveyor belts Tarpaulins Chemical hoses Ventilation ducts Rotor vanes	*Personnel protection* Bullet-proof body armour Flak-jackets Helmets Work gloves Nuclear shelters
Marine Boat hulls Rigging Canoes Coated fabrics Sails	*Sporting goods* Hockey sticks Tennis racquets Golf clubs Fishing rods Skis

problem for the structural applications is the difficulty of jointing such sections into structural assemblies; this is proportionally more difficult for aramids than for the weaker glass fibres. Such details are beyond the scope of this chapter, but can be found elsewhere.[39]

44.5.1.2 Reinforcing fibres for concrete

There has been considerable work carried out on the use of synthetic fibres for reinforcing concrete, and some of this work has included the use of aramid fibres.[40–42] However, for a variety of reasons, they are not suitable for this application. One of the few environments that cause degradation of aramid fibres is strongly alkaline aqueous solutions, and this is just the situation in a concrete mix. Even when the concrete has cured and most of the free water has evaporated, it is still likely that the environment will remain aggressive to the fibres. The different structure of Technora fibres, which may make them less permeable to hydroxide ions, is likely to mean that they are more resistant to this form of attack than Kevlar: indeed, floor slabs in office blocks in Japan have been built with concrete reinforced in this way.

As with all synthetic fibres, however, the benefits in using them to *reinforce* concrete are marginal, since concrete cracks at about 100 $\mu\varepsilon$, at which strain aramid fibres are carrying less than 1% of their breaking load.[43] There is some evidence that synthetic fibres assist in reducing cracking in concrete, probably as a result of the prevention of micro-cracking during hardening. It is unlikely that the strength, stiffness or resistance to creep of aramid fibres would offer significant advantages over cheaper fibres such as polypropylene, so this is unlikely to be a practical application of aramids.

44.5.1.3 Reinforcing cages for concrete

An interesting product has been tested recently in Japan, and is starting to come into experimental use in practical applications.[41,44] The aim is to make a preformed reinforcing cage for concrete, using straight longitudinal aramid fibres, with looped fibres in both the vertical and horizontal directions to resist shearing forces. The whole assembly is sprayed with epoxy resin to prevent the alkaline cement coming into contact with the fibres, and to give it some rigidity for handling purposes: the appearance of the cage is like three-dimensional knitting.

Three-dimensional grids for reinforcing beams, and two-layer grids for reinforcing slabs have been produced. The cages would only allow 10-mm aggregate to be used, and the difficulty of placing concrete in the confined spaces must be considered. However, these considerations are probably matters of site practice that can be overcome.

Test results produced for this system show that it has considerable promise as a reinforcing material, although more test data are required before it can be regarded as a suitable material for general use, particularly as regards its resistance to cracking at relatively low loads.

44.5.1.4 Pretensioning bars for concrete

Two manufacturers are producing pretensioning tendons for prestressed concrete using pultruded aramid fibres in a resin matrix. Akzo produce Arapree using the high-modulus version of Twaron, while Teijin produce AFRP (aramid fibre reinforced plastic) rod using Technora. Both systems reflect the properties of their constituent fibres.

Arapree is usually used in the form of flat strips,[45] and has been used as pretensioning tendons in the vertical posts of noise barriers on a Dutch motorway (shown in *Figure 44.5*), and in prestressed floor planks in an experimental 'house of the future' that has been constructed in Holland to demonstrate a variety of new engineering techniques. As with all pretensioning tendons, the system relies on bond between the concrete and the tendon, which must reflect the properties of the resin matrix,

Figure 44.5 Noise barrier posts pretensioned with Arapree tendons. (Courtesy of Akzo)

rather than the fibres. An external anchor, which relies on two flat wedges gripping the sides of the strip, is used to tension the tendons, and could also be used for a permanent end anchorage.

One of the problems with such pultruded systems is that the fibres, and hence the tendons, are brittle. If the tendon is fully bonded to the concrete, the tendon must undergo the same strain changes as the concrete, which in areas of high bending could produce failure of the tendon and hence brittle failure of the complete structure. Experiments are known to be underway to control the amount of bond between the tendons and the concrete by varying the texture of the surface and properties of the resin.[46]

AFRP rods are normally in the form of circular bars with diameters between 3 and 8 mm, although a flat strip version is also produced. They are designed to be used as bundles and the manufacturers have developed wedge systems to anchor the bars to a terminal, but they can also use resin mortar to bond the tendons to the end block. Experimental beams have been constructed, but it is not believed that any practical applications have been produced. These rods could also be used as pretensioning tendons in the same way that Arapree is used.

44.5.1.5 Parallel lay ropes (Parafil)

The final method for the use of aramids in civil engineering is in the parallel-lay rope; one such product (Parafil) has been developed by Linear Composites Ltd.

In conventional braided or twisted rope construction, individual fibres follow very complicated three-dimensional paths along the rope. This leads to a significant reduction in the axial stiffness of the rope; effective moduli can be as low as 30% of the fibre modulus. In structural applications, which are often stiffness governed, such reductions in properties would be unacceptable.

This problem can be overcome by the use of parallel-lay ropes, which consist of a large number of parallel yarns of the core material; since they are not twisted or braided in any way, they must be contained within a sheath of some form to maintain integrity. In the case of Parafil (*Figure 44.6*), this sheath is usually a low-modulus polyethylene. A variety of core yarns can be used in these ropes; the original ropes used polyester fibres, and were designed for mooring buoys in very deep water; they have also been used extensively for the stays on radio antennae.[32] With the advent of the aramid fibres, new versions of the ropes have been produced to exploit the higher strength and stiffness of these fibres.

The properties of the rope mirror those of the core yarns. Since every fibre in the core is effectively straight and continuous from end to end of the rope, the strength, stiffness, creep, relaxation and thermal properties of the ropes are virtually the same as those of the core yarns. The yarns are, however, slightly variable, and since any individual yarn will fail when the strain in the rope reaches the failure strain of that yarn, it is found that assemblies of variable fibres are not as strong as the mean strength of the fibres themselves. Such a result, which is adequately predicted by bundle theory,[47,48,64] leads to a quoted strength for the Parafil ropes of 1926 $\mathrm{N\,mm^{-2}}$, as compared with about 2700 $\mathrm{N\,mm^{-2}}$ for the multi-filament yarns and about 3500 $\mathrm{N\,mm^{-2}}$ for the individual filaments themselves. Small ropes (i.e. <6 tonne breaking load) are stronger than this,[49] but the quoted strength is applicable for all large ropes that have been tested (up to 1500 tonne).

The termination system that has been developed for the ropes consists of an internal wedge (or spike) which provides a radial gripping force between the spike and the external body, so that all the fibres are anchored.[32] The length of the spike can be chosen to ensure that the transverse stresses are within the capacity of the fibres. As with the rope itself, there is no need to introduce resin anywhere in the termination. Many tests have been carried out on the rope fitted with this type of termination, and in virtually all cases failure occurs within the body of the rope, indicating that the termination can develop the full strength of the rope.

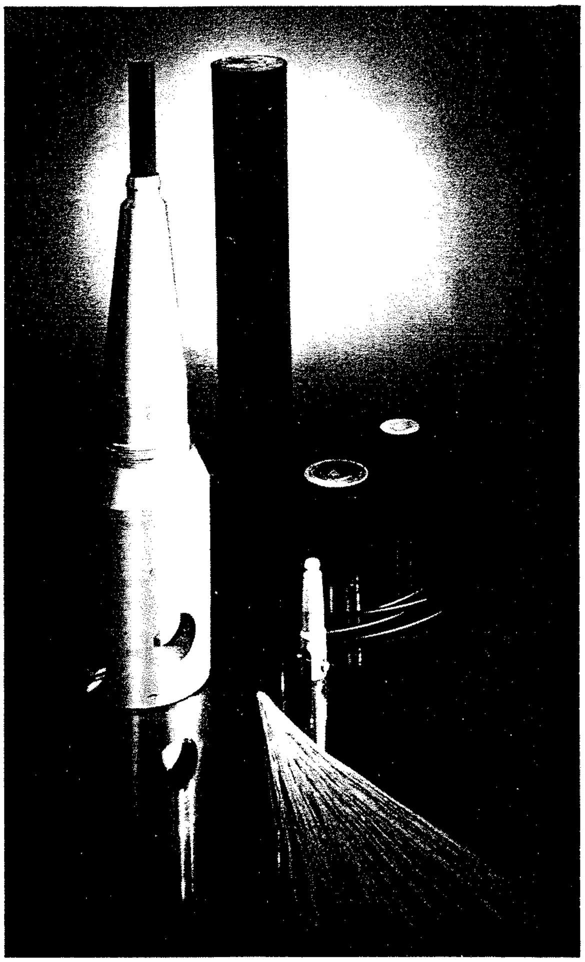


Figure 44.6 Parafil ropes and terminations. Largest rope shown is 140 mm in diameter with a breaking load at 1500 tonne. (Courtesy of Linear Composites Ltd)

Once the load has been transmitted from the fibres to the terminal body, further connection to the structure can be made by fitting a variety of devices, such as clevis pins, anchorage plates, or whatever is required. *Figure 44.7* shows such a terminal modified for use as a prestressing tendon.[50] The terminal body has two threaded regions: the inner thread is used for connection to a pull rod which is attached to the jack during stressing, while the outer thread is used to provide a connection for a permanent back nut, which also allows some adjustment to take account of slack. The anchorage is capable of achieving the full strength of the rope. Reasonable care must be taken to ensure that the spike is fitted centrally within the rope (to ensure even load sharing between fibres), but otherwise no special skills are needed.[51] Anchorages for parallel-lay aramid ropes with capacities between 1 and 1500 tonne have been provided using this system. All the results quoted here have been obtained on ropes fitted with anchorages in this way.

It is normal practice, where practicable, to preload the rope to ensure that the central spike is fully drawn into the

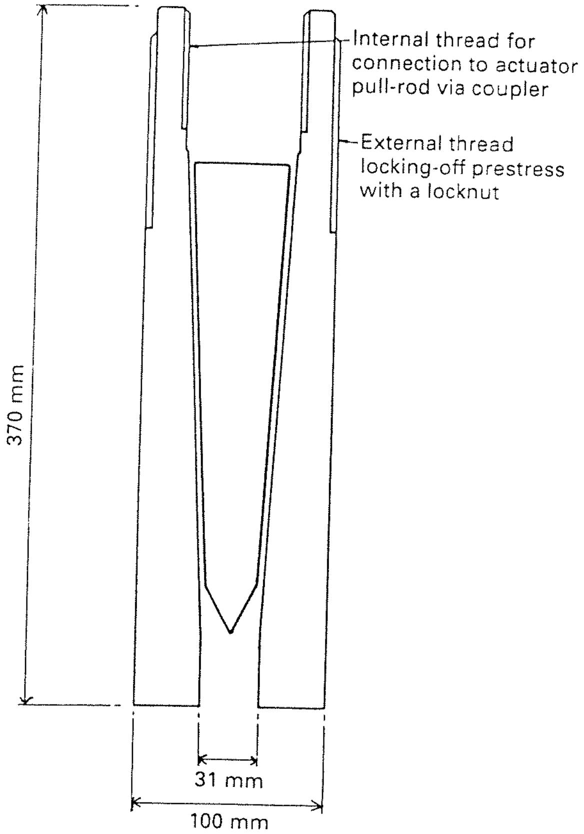


Figure 44.7 Section through a terminal for a 60 tonne Parafil rope, modified for connection to a jack for use in prestressing tendons

termination. This makes sure that no subsequent movement occurs in the termination, either on loading or unloading.

The ropes are versatile, and can be made with breaking loads from about 1 tonne up to several thousand tonnes. Thus, a variety of applications can be considered where it is required to carry a concentrated tensile force by a mechanism which offers a combination of high stiffness, low weight, high durability or insulating and non-magnetic properties.

Clearly, prestressed concrete, particularly with external tendons, is such an application, and a variety of test beams have been produced[4,5,65] (*Figure 44.8*). In all cases, failure occurred in the concrete, rather than in the tendons, since the unbonded geometry means that the tendons do not pick up significant additional strain. Quite large cracks can open up in the concrete, producing a composite material with an ability to absorb large amounts of energy.

One application of Parafil that typifies its potential, both for use as external prestressing and for repair of concrete, is the repair of faulty cooling towers at Thorpe Marsh power station in Yorkshire.[52] These towers were built in the early 1960s, but were recently found to have major cracks at the top. One tower had two vertical cracks, 12 m long and approximately 60 mm wide, which descended from the top ring beam. The towers were repaired by resin injection of the cracks, followed by circumferential prestressing of the towers with Parafil tendons, as shown in *Figure 44.9*. The aramid tendons were beneficial in several ways, since alternative steel tendons would have been too heavy for installation by steeple-jacks, and the exposed environment would have meant either extensive corrosion protection, or the use of very expensive stainless-steel tendons.

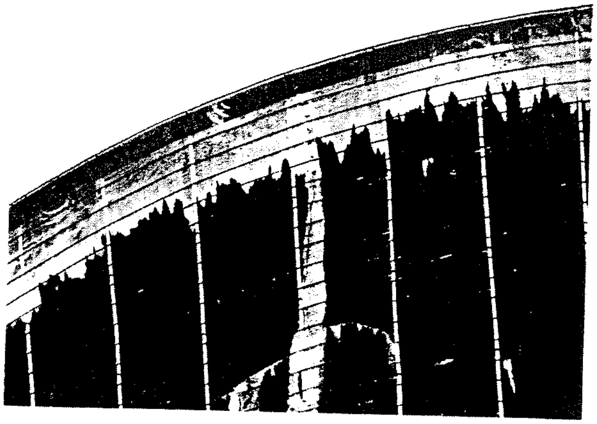


Figure 44.8 Circumferential external prestressing using Parafil ropes at the top of a cooling tower at Thorpe Marsh Power Station. (Courtesy of Central Electricity Generating Board)

Many other applications, to a variety of structural problems, are under active consideration.[52] These typically relate to cases where steel is unsuitable because it corrodes (such as in external prestressing,[53] and repair of existing structures), where inspection is impossible (such as in ground anchors and other foundation structures), or in cases where the electromagnetic properties of steel are unacceptable (such as in communications antennae and certain defence applications). Although the weight of the tension elements is rarely a governing factor in conventional prestressed concrete structures, the low density is also important when considering the tension members in lightweight structures,[54] and becomes a governing factor in mooring lines for deep-water oil exploration rigs[55] and in the suspension cables for very long span bridges.[56]

Recent surveys of the stay cables in bridges[57,58] have shown that steel cables are very likely to corrode, and the failure of steel tendons in bridges[59] where they are supposedly well protected by the alkaline environment provided by concrete shows that existing structures may have serious problems. Moves towards realistic 'whole-life costing' for bridge structures are likely to mean that apparently more expensive aramid cables become cost effective in the long term.

It is possible to envisage new forms of solution to existing problems that become possible with the use of aramid tension members. Many of our preconceptions of the way structures should be designed come from the need to protect steel members from corrosion. Thus, we embed prestressing tendons in concrete, especially in marine environments, but open structures in which sea- or ground-water are free to flow around the prestressing tendons can easily be envisaged. Similarly, we can consider prestressed brickwork, with the tendons in voids within the structure, or, in the case of retaining walls, even in the backfill behind the walls. Ground anchors can also be designed without the need to make large allowances of sacrificial material to allow for corrosion.

Very long span suspension bridges are also likely to be a suitable use for these new materials. It has been concluded[60] that spans of 3 km or so were possible using steel suspension cables, but that for larger spans aramid cables of the Parafil type would be necessary, since the high density of steel means that for very large spans much of the strength of the steel is taken up supporting its own weight. The current longest single span is the Humber Bridge (1.4 km), but the Akashi bridge in Japan on which work has just begun will have a span of 1.9 km. However, it is reported that extreme difficulties were experienced

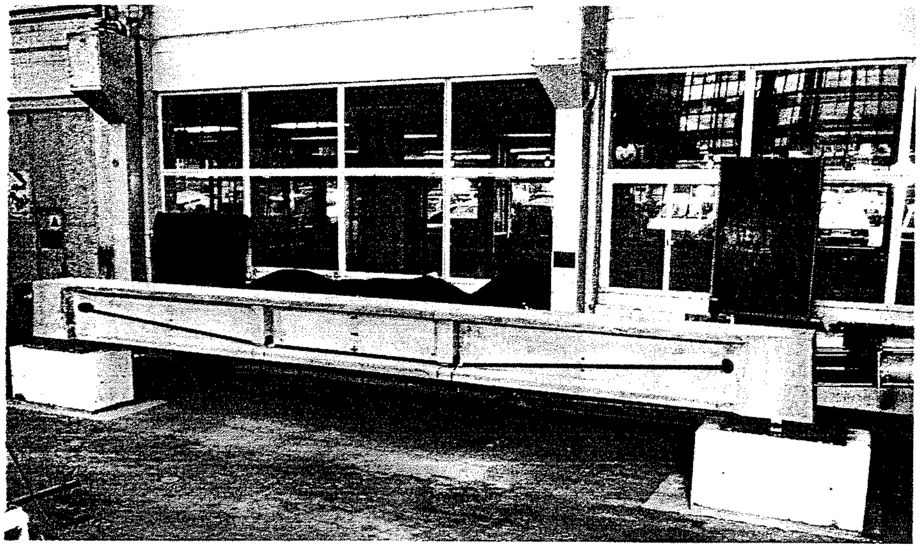


Figure 44.9 Concrete beam with a span of 8 m, prestressed with two 60 tonne Parafil ropes. (Courtesy of Imperial College)

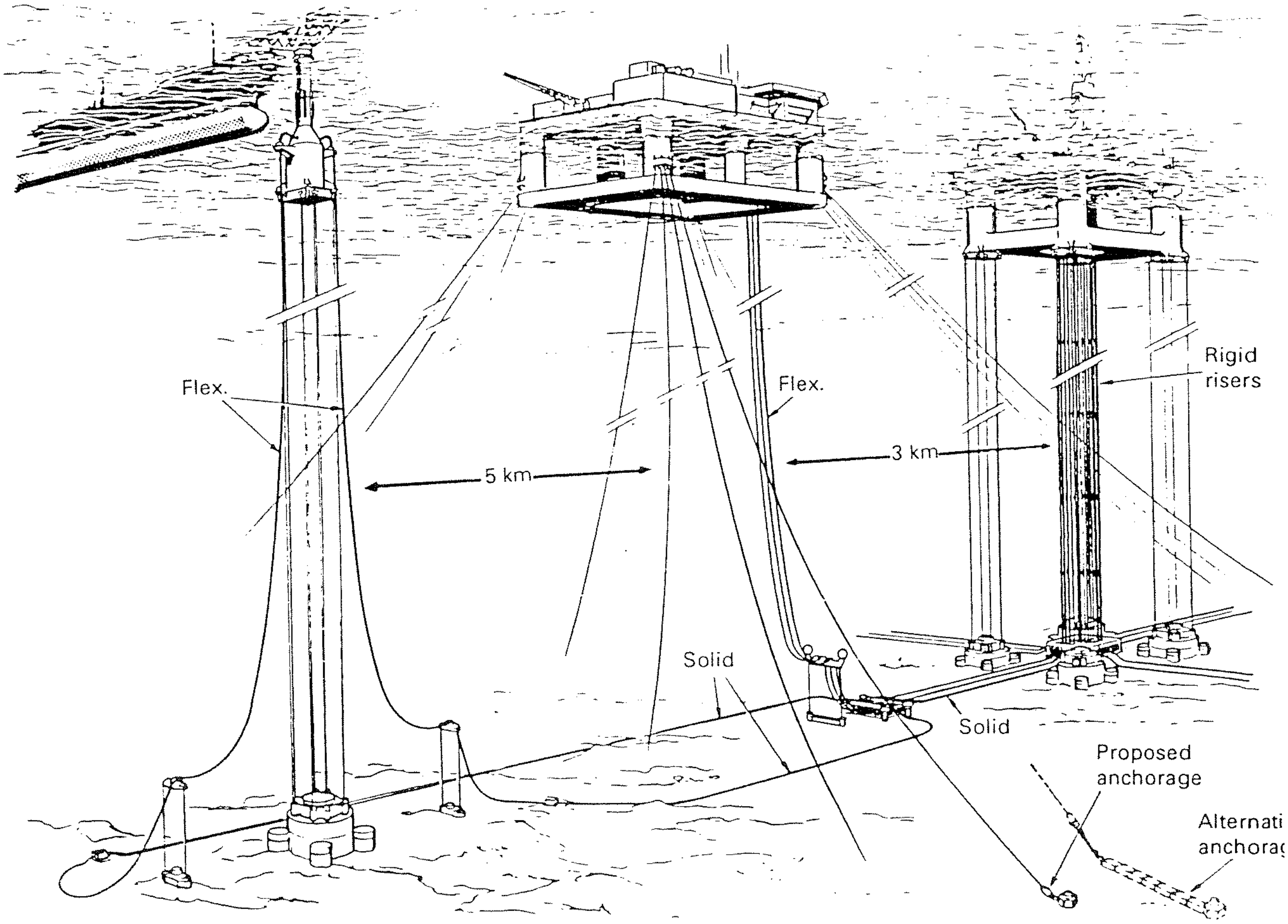


Figure 44.10 Possible configuration for offshore oil production installation in very deep water, using parallel-lay aramid ropes as tethers and anchoring ropes

in getting suitable steel for the main cables,[61] and special products had to be designed, so it is possible that the true 'break-even' point where aramid fibres will become competitive is at spans below 3 km.

A number of problems will have to be overcome for very large spans, but these relate to the aerodynamic stability of the structure, and would be a problem for any material used in long spans. It is possible that designs for large-span suspension bridges will incorporate an element of self-stressing, in which one cable is tensioned against another, or possibly the use of a number of draped cables, so that no deformation of the structure is possible without inducing direct tension in at least one of the supporting cables.[62]

In very deep water the difficulties of anchoring large platforms for exploration or production of oil have been recognized. In water depths of up to 500 m it is possible to design jacket structures which stand on the sea-bed, but in larger water depths, where exploration is now beginning, the structures will have to float. It has been concluded that steel tethers are simply too heavy for large water depths, since the platform would have to have a large amount of buoyancy simply to support the weight of the anchoring system.[55] Aramid tendons using Parafil ropes, which are almost weightless in water, provide a means of anchoring such structures in a manner which is almost independent of the water depth. A recent study has concluded that the tendons can be produced in a mobile factory on-shore, but close to the desired location. Complete anchorage assemblies can then be produced and floated into position, giving very rapid hook-up of the floating structure to the sea-bed facilities.[63] This offers considerable savings in installation costs, which is very often one of the most difficult things to control in offshore operations. *Figure 44.10* shows a number of different concepts that have been considered for the mooring of a variety of platform types in very deep water.

44.6 Conclusion

Aramid fibres have a very remarkable set of properties, which will make them suitable for many applications in a variety of fields. With strengths similar to cold drawn steel, stiffnesses of the same order and with good resistance to corrosion, we can expect to see these materials being adopted in many ways in the future, either as fibres, pultrusions or parallel-lay ropes.

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Appendix

The following is a list of the trade names used in this chapter.

Nomex and Kevlar are trade names of E.I. Du Pont de Nemours.
Twaron is a trade name of Aramide Maatschappij vof.
Arapree is a trade name of Akzo and Hollandsche Beton Groep.
Technora is a trade name of Teijin.
Parafil is a trade name of Linear Composites Ltd.